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Systems Engineering Approach and Metrics for Evaluating Network-Centric Operations for U.S. Army Battle Command

by Jock O. Grynovicki and Teresa A. Branscome

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14. ABSTRACT

While many studies have taken a traditional task-analysis approach to assessing the effects of technology on battle command performance, this report describes the implementation of a global systems approach for examining usability, functionality, and performance from operator, commander, staff, and organizational perspectives. The approach had three steps: the first step was identifying tasks and behavioral characteristics that were associated with effective battle command performance at the operator, commander and staff, and organizational levels; the second step was developing a framework for measuring how well technology provides the usability, functionality, and performance required at each of the three levels; the third step was developing metrics and tools to implement the measurement framework. This approach has been used successfully to assess technology ("digitization") effectiveness by the U.S. Army Training and Doctrine Command and the Operational Test Command during network integration evaluations, limited user tests, and initial operational test and evaluation. This report describes the three-step approach and presents data demonstrating the reliability of the questionnaire as it was used to evaluate the Advanced Field Artillery Tactical Data System version 6.5.0.

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Contents

List of Figures

List of Tables

1. Introduction

As part of the transformation and modernization process, the U.S. Army has sponsored experiments ranging from large-scale experiments and evaluations (Advanced Warfighting Experiments [AWEs] and Network Integration Evaluation [NIE]) to smaller Advanced Technology Demonstrations (ATDs) that evaluate the maturity of a technology and assess its potential application to a military need. This research supports the integration of Soldier operators, maintainers, and trainers with weapons, vehicle, and communications systems.

Field experimentation provides important insights in this regard, for many of the operational and human factors issues affected by technology do not appear in isolated tests. Rather, the full implications, limitations, and strengths of a system emerge only when that system is employed in concert with other systems under demanding field conditions. As a result, field experimentation represents an important tool for assessing the interoperability of new systems with existing systems and functional areas.

For field experimentation to be effective it is important to have a measurement framework and corresponding instrumentation to assess how well new technology impacts operator, staff, and organizational performance. To meet this need, one goal of the U.S. Army Research Laboratory's (ARL's) Human Research and Engineering Directorate (HRED) is to support the Human Dimension (HD) Major Laboratory Program (MLP). HD was formalized by the U.S. Army Training and Doctrine Command (TRADOC) and is a major Army effort designed to support evaluations of the integration between Soldiers and communications systems, weapons, and vehicles (*1*).

HRED is responsible for evaluating Soldier-system performance to make certain Soldiers are equipped with systems they can operate proficiently with minimal risk. A major objective of this effort has been to develop and execute a systems engineering approach along with standardized field-operational Soldier performance metrics to quantify and validate integrated Soldier-information systems performance on the digital battlefield.

The current HD effort involves expanding previous Human Factors (HF) metrics and analyses to develop an understanding of how the commander and the battle staff use all the Army Battle Command System (ABCS) and Network Operation subsystems to support effective battle command. This effort began with a task analysis, but moved to a more total systems perspective considering how effectively new technology supported the commander and staff and, more generally, fit the operational needs of the larger organization from a Soldier in a Squad to one in the Division. The purpose of this paper is to describe this approach, with an emphasis on the measurement framework and psychometric properties of the questionnaire developed thus far from this research. The framework and questionnaire have been used successfully to support

NIEs, Limited User Tests (LUTs), Initial Operational Test and Evaluation (IOT&E), Advanced Warfighting Experiments (Joint Contingency Force, Division Capstone Exercise I and II), and related Force XXI and Army Transformation activities.

2. Approach

We used a three-step approach to move from a task-based to a more global systems approach for examining usability, functionality, and performance from operator, commander and staff, and organizational perspectives. The first step was identifying tasks and behavioral characteristics that were associated with effective battle command performance at the operator, staff, and organizational levels. The second step was developing a framework for measuring how well technology provides the usability, functionality, and performance required at each of the three levels. And the third step was developing questions using Likert scales, cue cards and tools to implement the measurement framework. This section briefly describes this three-step approach. The following section presents data demonstrating the questionnaire's reliability when used to evaluate the Advanced Field Artillery Tactical Data System (AFATDS) version 6.5.0.

2.1 Step 1: Moving From Tasks to Consider the HD of Battle Command

We began by using the Universal Joint Task List (UJTL) (*2*) to identify essential Command and Control (C2) tasks. The UJTL is organized into four separate parts according to the level of war: (1) Strategic level—National military tasks, (2) Theater-level tasks, (3) Operational-level tasks, and (4) Tactical-level tasks. Each task in the UJTL is individually indexed to reflect its placement in the structure. Thus, the UJTL provides a standard reference system for users to address and report requirements, capabilities, or issues and as such formed the command staff task baseline around which ARL developed its standardized Soldier performance metrics research.

However, battle command itself is a process conducted by an organization consisting of system operators, Soldiers, battle staff, and leaders in a tactical environment working toward a common goal. To assess digital battle command and network operations system performance and effectiveness, one must understand battle command as a human process that involves the complex interaction of cognitive and socio-organizational factors supported by digitization and the environment (see figure 1). Such assessments move beyond simple task level descriptions of battle command and involve the need to investigate specific battle command organizational proficiencies.

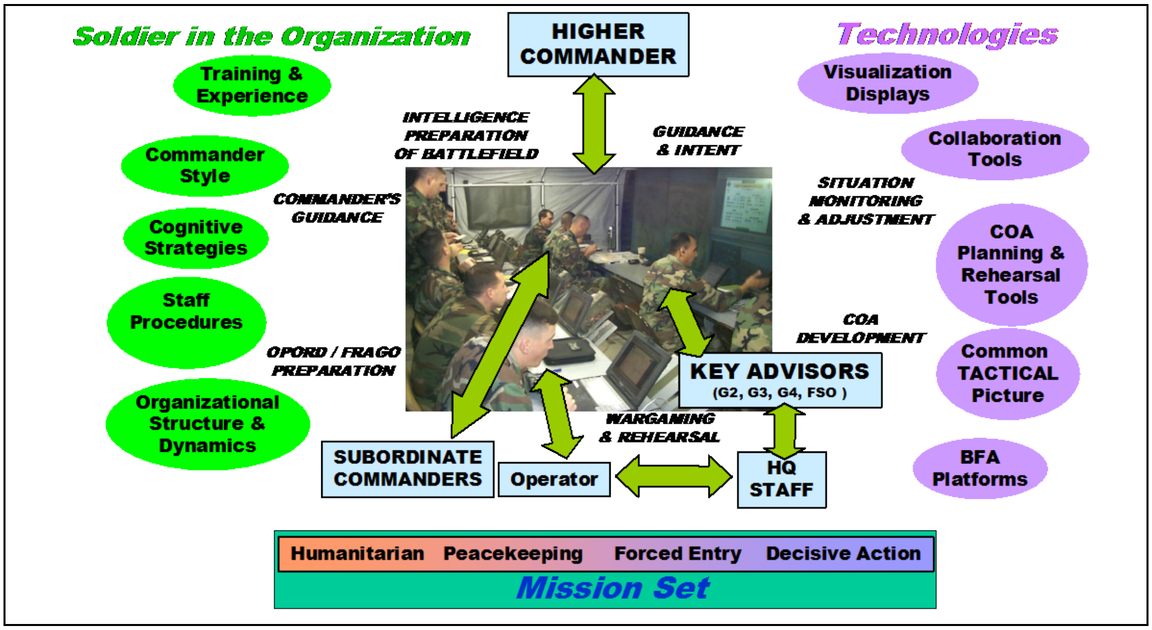

Figure 1. Total systems engineering approach (variables influencing battle command).

These proficiencies are reflected in specific patterns of organizational, staff, and operator-level behaviors that allow the sequence of decision-making tasks associated with battle command to be carried out effectively, efficiently, and with an appropriate level of adaptability to different mission sets. To better understand these behaviors, ARL developed a survey based on staff proficiencies focusing on the interrelationships between staff functions or processes required for effective C2 decision making. In particular, ARL's survey metrics methodology established a cross-linking of FM 101-5 (*3*) military decision-making processes (MDMP) with the ABCS software modules thought to support critical command and staff task execution. FM 101-5 states that a staff supports the "science of control" in four primary ways: (1) gathers and provides information to the commander, (2) makes estimates of the set of actions required, (3) prepares plans and orders, and (4) measures organization behavior. To perform this type of support, the staff and commanders use various time-dependent decision making and information management processes that require extensive staff coordination between and within echelons. It was assumed that the ABCS and network operations subsystem software function capabilities were developed to support these human-centered C2 processes and avoid errors in judgment and timing. Based on the survey and guidance from TRADOC, 12 HDs of digitized battle command operations (figure 2) were selected from which to extend the previously developed HF measurement framework so that it also would measure the effects of technology on the HDs of battle command.

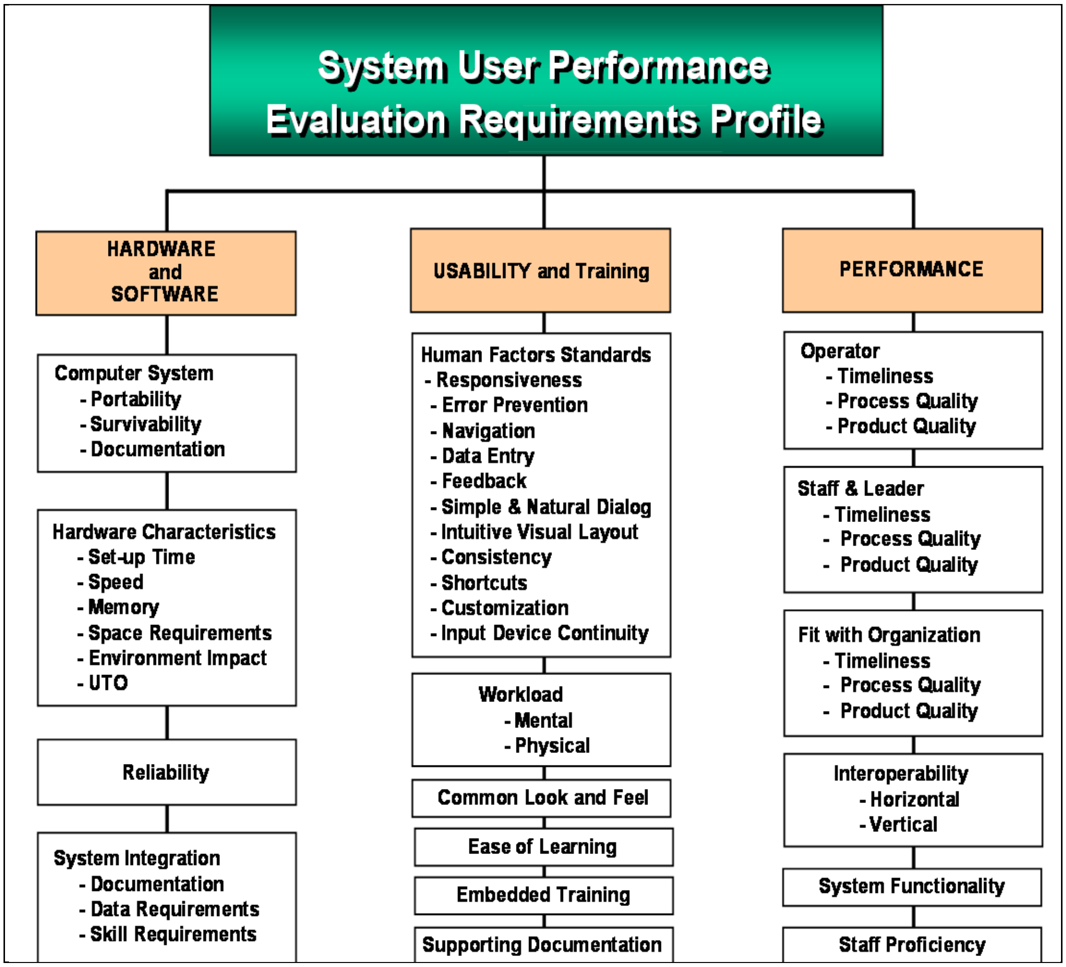

Figure 2. Three human factors areas of digitization system assessment.

2.2 Step 2: Measurement Framework

As a lead agency for Human Factors Integration, ARL participated in the performance evaluation of new versions of the ABCS during several NIEs and operational tests. The NIEs are evaluations of emerging systems in operational scenarios that allow us to demonstrate interoperability early in the development life cycle. A set of performance metrics was developed to support those evaluations. These metrics were based on the measurement framework shown in figure 2, which was built after completing step no. 1 in our previously described systems engineering approach.

The measurement framework (figure 2) is called the System User Performance Evaluation Profile, or Profile for short. This framework and corresponding questions used to implement it were used to collect data to determine if the ABCS met operator, commander and staff, and organizational objectives and needs. These metrics represented the performance measures for the prototype operational system and were a key part of the system requirements validation process. The Profile has three branches of performance metrics. The first branch, called

Hardware and Software, represents conventional hardware and software test and verification criteria. Rushby (*4*) referred to them as the basic service requirements of a system. The service requirements or criteria in the Profile are important for military systems, and build upon an earlier set developed by Adelman and Ulvila (*5*). These criteria measure, for example, how portable the new system is from one location to another, how survivable it is, how good the documentation is, how easy the system is to set up and integrate with other systems, how fast and reliable it is, and so forth.

The second branch in the Profile measurement framework is the "usability and training factor." System usability has a direct impact on staff performance because shortcomings in system usability lead to underlying error patterns, attention deficits, and excessive workload which can be linked to inappropriate decisions and priorities, serious delays in operational tempo, and failures in effective staff coordination and communications. The usability of the metrics was guided by human-computer system issues that have been described in the research literature (e.g., *6*, *7*) as reflecting hardware and software design with good interface usability. The usability characteristics included whether the computer system: (1) contains simple and natural dialogue, (2) applications reflect doctrine, (3) "speaks" the user's language, (4) minimizes user memory load, (5) remains consistent between different modules and across applications, (6) provides user feedback, (7) provides clearly marked exits from modules, (8) provides process shortcuts, and (9) prevents errors.

Additionally, questions regarding conventional human factors (HF) considerations (e.g., screen display contrast, symbol color, and screen layout) were also included in the survey. These criteria build upon an earlier set found in Adelman and Riedel (*8*). For in-depth specific HF design standards one can also refer to MIL Standard 1472-G (*9*). This standard establishes general human engineering criteria for design and development of military systems, equipment, and facilities.

The purpose of this standard is to present human engineering design criteria, principles, and practices to be applied in the design of systems, equipment, and facilities so as to: (1) achieve required performance by operator, control, and maintenance personnel, (2) achieve required manpower readiness for system performance, (3) achieve required reliability of personnel-equipment combinations, and (4) foster design standardization within and among systems (*9*).

The third branch of the Profile measures how well the system supports the battle command functions of the operator, staff and leader, and larger organization. This branch of the measurement framework builds directly on the HD research performed in step no. 1 of our systems engineering approach and utilizes some of the performance criteria found in Adelman and Riedel (*8*). In particular, the Performance branch measures the system's effect on the ability of the operator, staff and leader, and larger organization to perform their work in a timely way, and on the quality of their processes and resulting products. In addition, the Performance branch measures the system's interoperability with other systems, both horizontally and vertically within the organization. Lastly, it obtains overall measures of the system's functionality and effect on staff proficiency.

2.3 Step 3: Questionnaire for Implementing the Profile Measurement Framework

Questions were developed to measure the effect of ABCS system components on each of the criteria in the Profile measurement framework. The questions were designed so that only the name of the ABCS system component needed to be changed, thereby permitting the same questions to be used as metrics for evaluating all components. This permitted a standard frame of reference for measuring the components, so that the HF and HD effects of each component could be evaluated relative to other ABCS components. This approach has been used previously to evaluate the relative strengths and weaknesses decision support and expert system components (*10*).

Participants answered each question using a 5-point Likert scale. Their responses measured how well they thought the system performed on that metric. The questions were always written so that higher scores meant that the system was performing better on the metric. This was done so that respondents could complete the questionnaire quickly given the limited time available for data collection during the AWEs and not be confused by changes in the directionality of the wording of the question.

Two examples are presented in figure 3 for evaluating the Advanced Field Artillery Tactical Data System (AFATDS). Both questions measure AFATDS' effect on the staff and leader's process quality in the third branch of the Profile measurement framework. The first question measures AFATDS' effect on staff planning, and the second question measures AFATDS' effect on staff collaboration.

How user-friendly is the use of the AFATDS for fire support planning processing?

(1) Very Poor (2) Poor (3) Adequate (4) Good (5) Very Good

How user-friendly is it to use the AFATDS (White Board) for conferencing?

(1) Very Poor (2) Poor (3) Adequate (4) Good (5) Very Good

Figure 3. AFATDS questionnaire example.

3. Application

Questionnaires based on our systems engineering approach were developed to evaluate each component of the ABCS during exercises, as previously described. This section presents data showing the internal and inter-rater reliability of the questionnaire used to evaluate AFATDS, and demonstrates the technical adequacy of the measurement instrument. Similar technical analyses of the questionnaires for the other net-centric subsystems are currently underway and will be reported in later documents. We begin this section by presenting the requirements statement for ABCS and then provide a brief description of the role of AFATDS. After doing so, we present the reliability results for the questionnaire measuring AFATDS.

The U.S. Army Battle Command System Capstone Requirements Document (CRD), revision 3a (*11*) describes the objective system as follows:

> The objective ABCS will provide seamless real or near real time C4I capabilities which increase the lethality and information dominance of friendly forces from the strategic echelon to the foxhole across all spectrums of conflict. The ABCS will allow commanders to utilize dominant firepower systems more effectively to destroy enemy forces in an extended area of operations while protecting friendly forces. The firepower will be enhanced by providing the commander the ability to make quicker, more accurate decisions, and orchestrate combat power at critical times and places faster than an adversary. Additionally, the ABCS will enhance SA and enable friendly forces to share a CTP while communicating and targeting in real or near-real time. The ABCS will reduce the uncertainty of war situations, decrease decision-making time, and contribute to increased lethality, survivability, and operational tempo while reducing the potential for fratricide. The objective ABCS will be computationally intensive not communications intensive. It will employ a common computer architecture and communications hardware, a core set of common support software, and software which is functionally unique to each sub-system.
>
> ABCS is an evolving "system of systems" that needs individual subsystem testing and evaluation. The entire family of systems will be assessed individually and collectively to ensure that the functional requirements are met as well as the overarching commander decision-making and human dimension requirements contained in this document.

The Advanced Field Artillery Tactical Data System is the fire support component of ABCS and provides automated decision support for fire support (FS), to include joint and combined fires (*12*). AFATDS supports the planning, coordination, control, and execution of close support, counter fire, interdiction, deep operations, and suppression of enemy air defense. It is a single integrated fire support asset manager. It provides decision aids and an information system for the synchronization of all types of fire support means.

4. AFATDS Questionnaire Validation

This section presents data regarding the internal and inter-rater reliability of the questionnaire used to evaluate AFATDS. The internal reliability (or consistency) of the questionnaire was measured by the Cronbach Alpha statistic. This statistic is based on the premise that if one has successfully sampled items from the hypothetical population of items measuring the same construct, then the responses to these items should be correlated highly. The inter-rater reliability of the questionnaire was measured by correlating the respondents' answers to the questions. The correlations were calculated to determine the extent of agreement among the respondents. Consistent with Gable and Wolf (*13*), the goal was to ensure that the questionnaire had high internal consistency and then determine if there was high agreement (or disagreement) among the respondents about the value of AFATDS.

Fifteen AFATDS operators completed the questionnaire, providing an adequate number of users. The calculated Cronbach Alpha value was 0.81. Since this value was higher than 0.70, which is routinely used as the necessary Chronbach Alpha value (*13*), we concluded that the AFATDS questionnaire had an acceptable level of internal reliability.

Table 1 presents the inter-rater reliability correlations among the 15 respondents. (Respondents R04 and R10 did not complete the questionnaire.) The correlations are Pearson product-moment correlations, which can range from +1.0 indicating perfect agreement to –1.0 indicating perfect disagreement. A Pearson product-moment correlation (r) of 0.39 is significantly different than a correlation of 0.0, which means no agreement, at the p = 0.05 (alpha) level for a t-test with 17 degrees of freedom, two less than the number of questions. Eight of the 15 respondents (R01, R02, R03, R05, R06, R08, R12, and R15) had significant inter-rater correlations ($r \geq 0.39$) with every other respondent; that is, for all 14 comparisons. And three other respondents (R07, R11, and R14) had significant comparisons for 13 of the 14 possible comparisons with all other respondents. So, in total, 73% (11 of 15) of the AFATDS respondents had at a minimum of 13 out of a possible 14 (93%) significant comparisons (inter-rater correlations). This means that the large majority of the responding AFATDS operators significantly agreed with each other when using the questionnaire to evaluate AFATDS, and that the questionnaire had an adequate level of inter-rater reliability.

In general, we thought that the level of agreement was moderate, not high. To reach this conclusion, we assumed that a "high" correlation had to be at least 0.71 because that correlation would account for 50% of the variation between two respondents' scores. Only three (20%) of the respondents (R01, R02, and R12) had 7 or more inter-rater correlations ≥ 0.71 for the 14 possible comparisons. Since 73% of the respondents had significant correlations ($r \geq 0.39$) for at least 13 of their 14 comparisons, but only 20% had high correlations ($r \geq 0.71$) for 50% of their comparisons, we concluded that there was, in general, a significant but only moderate level of agreement among the responding AFATDS operators. Nevertheless, the questionnaire met the requirements for inter-rater reliability.

Table 1. AFATDS correlation matrix for inter-rater reliability.

Resp	**R01**	**R02**	**R03**	**R05**	**R06**	**R07**	**R08**	**R09**	**R11**	**R12**	**R13**	**R14**	**R15**	**R16**	**R17**
R01	1.00	–	–	–	–	–	–	–	–	–	–	–	–	–	–
R02	0.84	1.00	–	–	–	–	–	–	–	–	–	–	–	–	–
R03	0.70	0.66	1.00	–	–	–	–	–	–	–	–	–	–	–	–
R05	0.79	0.71	0.52	1.00	–	–	–	–	–	–	–	–	–	–	–
R06	0.80	0.81	0.59	0.59	1.00	–	–	–	–	–	–	–	–	–	–
R07	0.64	0.60	0.52	0.45	0.60	1.00	–	–	–	–	–	–	–	–	–
R08	0.67	0.65	0.82	0.42	0.68	0.59	1.00	–	–	–	–	–	–	–	–
R09	0.65	0.66	0.44	0.46	0.77	0.48	0.54	1.00	–	–	–	–	–	–	–
R11	0.75	0.71	0.48	0.58	0.60	0.79	0.55	0.58	1.00	–	–	–	–	–	–
R12	0.80	0.84	0.67	0.60	0.82	0.77	0.74	0.61	0.79	1.00	–	–	–	–	–
R13	0.69	0.62	0.42	0.44	0.66	0.57	0.41	0.41	0.64	0.69	1.00	–	–	–	–
R14	0.78	0.91	0.69	0.55	0.76	0.62	0.72	0.50	0.67	0.79	0.72	1.00	–	–	–
R15	0.77	0.71	0.64	0.49	0.68	0.74	0.52	0.52	0.68	067	0.75	0.69	1.00	–	–
R16	0.54	0.40	0.54	0.39	0.48	0.14	0.46	0.30	0.16	0.47	0.13	0.23	0.33	1.00	–
R17	0.64	0.75	0.57	0.48	0.60	0.54	0.63	0.39	0.45	0.67	0.60	0.80	0.59	0.23	1.00

It is also interesting to note that sometimes there was a very high level of agreement between two AFATDS operators. In particular, R02 and R14 had an inter-rater correlation of 0.91. This means that one essentially could use either of these two respondents to predict the ratings of the other. At the other extreme, R13 and R16 had an inter-rater correlation of only 0.13, indicating that they hardly agreed with each other at all. Since the results reported above indicate that the questionnaire has acceptable levels of internal and inter-rater reliability, future research will try to more fully understand why operators disagree with each other when evaluating the same ABCS components.

5. Conclusion

This report describes the systems engineering approach that ARL has used to develop performance metrics for evaluating digitization for the U.S. Army Battle Command. The approach emphasized measurement of system effects on the human dimensions of battle command at the operator, commander and staff, and organizational levels. The measurement framework assessed digitization usability and performance as well as traditional hardware and software verification criteria. The questionnaire developed to implement the framework has passed the requirements of internal and inter-rater reliability. Future research will make use of the questionnaire to evaluate other ABCS components and identify ways for improving not only those components, but also our overall measurement approach.

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